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Path Following of Underactuated Marine Vehicles Based on Model Predictive Control

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Straight line path following of the underactuated ONR Tumblehome ship in the presence of ocean currents is studied. The maneuvering modeling group (MMG) model is used to simulate the motion of the vehicle, and a linearized model is constructed for controller design. A guidance strategy combining the line-of-sight (LOS) and integral line-of-sight (ILOS) guidance laws is proposed to compensate for the drift effect. Furthermore, to deal with the saturation of rudder angle and limitation of maximum rudder rate explicitly, the model predictive control (MPC) technology is utilized. Simulations are conducted, and the results show good path following performance of the guidance-based MPC controller.

INTRODUCTION

Path following is one of the key issues for surface ships to accomplish their missions autonomously, which shows broad application prospects in civilian and military fields. Although path following of underactuated ships has been studied extensively in the past few years, the underactuated nature of surface ships coupled with the nonlinear characteristics of ship maneuvering motion, especially under the unknown external environmental disturbances, makes the path following problem rather challenging (Martelli et al., 2014).

Marine vessels rely on the reference trajectory generated by the guidance system to accomplish desired motion control tasks (Breivik, 2010). Among the guidance methods for the path following of underactuated marine ships, the line-of-sight (LOS) guidance law can convert the single-input/double-output (SIDO) problem into a single-input/single-output (SISO) problem effectively (Fossen et al., 2003). This method circumvents the underactuated problem by mimicking an experienced helmsman and generates a reference trajectory for the yaw angle. However, as Borhaug et al. (2008) and Lekkas and Fossen (2014) pointed out, although traditional LOS guidance law has several good properties and is widely used in practice, it has the drawback of being susceptible to environmental disturbances such as winds, ocean currents, and waves. To make up for this drawback, a few modified methods based on the conventional LOS guidance law have been proposed, such as those in Borhaug et al. (2008), Lekkas and Fossen (2014), Caharija et al. (2016), and Fossen and Lekkas (2017). In these modified versions of LOS guidance law, an integral term is introduced to the algorithm, named integral line-of-sight (ILOS) guidance law, which can adaptively compensate for the drift effect caused by the constant or slowly time-varying external disturbances.

In path following applications for vessels with motion of three degrees of freedom (surge, sway, and yaw; 3-DOF) in the horizontal plane, the control objective is to follow a predefined path without setting temporal constraints. To design the controllers and test the anti-interference ability of the designed controllers under the constant ocean currents, Zhu et al. (2016) used three kinds of control algorithms: Proportion Integration Differentiation (PID), fuzzy PID, and fuzzy Proportion Differentiation (PD). Zheng and Sun (2016) investigated the path following of an unmanned marine surface vessel in the presence of uncertain disturbances and input saturation, and the ILOS guidance law was adopted. Based on the input/output feedback linearization method, Paliotta et al. (2018) proposed a control strategy in which the hand position point was used as output for trajectory tracking and path following of underactuated marine vehicles. Oh and Sun (2010) presented a model predictive control (MPC) method to deal with the input constraints, but they did not consider the external disturbances. Do et al. (2004) proposed a robust nonlinear control strategy based on Lyapunov's direct method and backstepping method; the model experiments were carried out later (Do and Pan, 2006). Inspired by Do et al. (2004), Li et al. (2008) proposed a more concise nonlinear controller by utilizing the passive-boundedness property of the sway motion. Niu et al. (2016) compared four common path following algorithms, including the carrot-chasing algorithm, nonlinear guidance law, pure pursuit and LOS path following, and vector field algorithms for an unmanned surface vehicle. The conclusion was that the nonlinear guidance law has the best accuracy in the presence of external disturbances.

The simulation model and the controller design model are the same in the aforementioned studies, and some of the simulation models are simplified models. However, in realistic implementations, the simulation model should be of high fidelity in order to imitate actual ship motion, while the controller design model should be as simple as possible under the premise of reflecting the main characteristics of the system to meet the real-time requirement (Martelli and Figari, 2017). Additionally, the control input (namely, the rudder angle) is limited by rudder angle saturation and maximum rudder rate. These constraints should all be taken into account explicitly during the controller design stage. The MPC acts as an optimization process and can take all of these physical constraints into consideration easily. Though the computation has improved greatly during recent years, the nonlinear MPC where the nonlinear optimization is required can still be nontrivial, which impedes the dissemination of the MPC technology. Nevertheless, compared with the classical PID control, the linear MPC shows some better properties, such as faster response and smaller overshoot, because of its rolling optimization and feedback correction.

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KEY WORDS: Path following, underactuated surface ship, ONRT, ILOS, MPC.